A preliminary water balance for the Colorado River delta, 1992 - 1998

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Water balances for the Colorado River mainstem complex, the Cienega de Santa Clara, and El Indio wetlands were calculated for the Colorado River delta in Mexico for the period 1992-1998. Discharge for the mainstem complex was disaggregated into flood and non-flood years, reflecting the marked variability of mainstem discharge at the Southerly International Boundary (SIB) delimiting the United States and Mexico. In non-flood years, agricultural and municipal returns to the mainstem below SIB contributed 180% of mainstem discharge at SIB, but may not be sufficient to generate the floodstage discharge required by native riparian vegetation.

Keywords: Colorado River delta; water balance; hydrology; agricultural drainage; riparian vegetation; wetland vegetation.

Introduction

The delta of the Colorado River, a remnant wetland located along the border of the Mexican states of Baja California and Sonora, is the subject of growing scientific and political interest. The recent literature on the ecology and restoration of the delta of the Colorado River emphasizes the importance of natural and anthropogenic sources of water for sustaining delta habitats (Glenn *et al*., 1992, 1996, 1999; Zengel *et al*., 1995; Morrison *et al*., 1996; Valdés-Casillas *et al*., 1998; Luecke *et al*., 1999; Pitt *et al*., 2000).

The delta, formed by the deposition of sediment from periodic Colorado River floods (Sykes, 1937), has been altered by the construction of upstream impoundments and the conversion of wetlands to irrigated agriculture, reducing the delta's extent from some 7,770 km^2 to 600 km^2 (Luecke *et al*., 1999). Prior to the construction of dams, diversions, and other reclamation projects, the mean annual discharge of the Colorado River water near Lees Ferry, Arizona, 1067 km upstream of the current extent of the delta, has been estimated at 17,000 x 10^6 m^3 (17 km^3) (Meko *et al*., 1995). Before upstream impoundments and diversions dewatered the Gila River, it contributed an estimated additional 1,600 x 10^6 m^3 year^{-1} to the discharge of the Colorado River, at its confluence near Yuma, 18.7 km upstream from the Northerly International Boundary (NIB) (U.S. Bureau of Reclamation, 1952). This combined discharge flowed through the Colorado River delta and into the Upper Gulf of California, supporting tremendous biological productivity and diversity (Luecke *et al*., 1999). Except in years with unusually high run-off, virtually the entire flow of the Colorado

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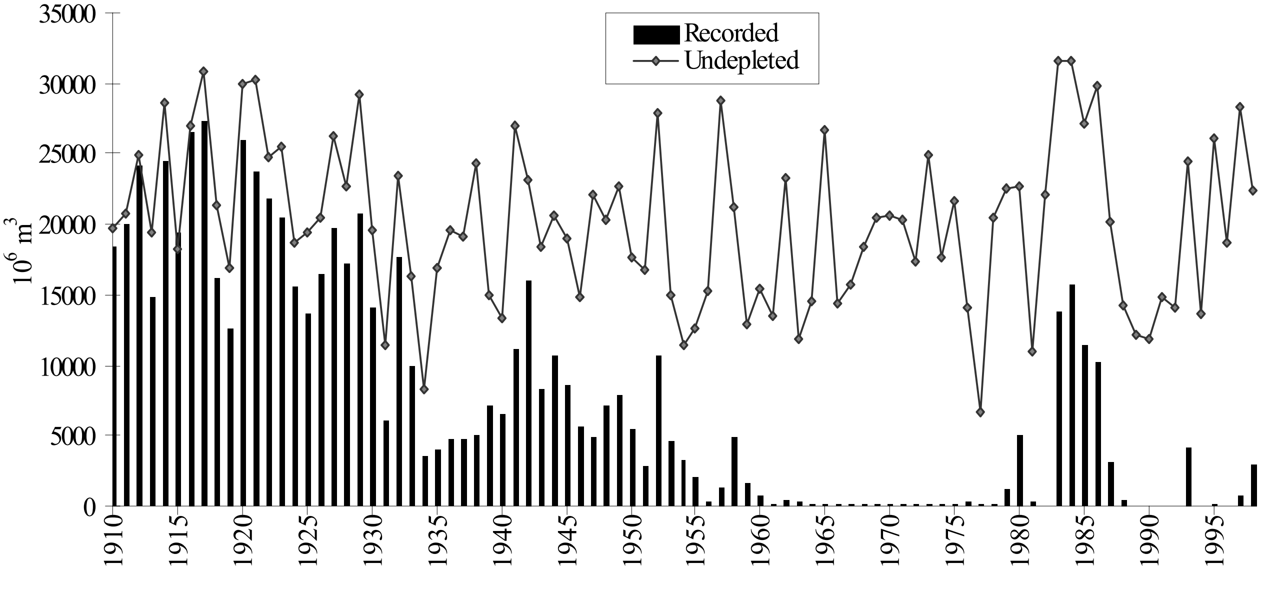

Figure 1. Colorado river discharge at the Southerly International Boundary (SIB) 1910–1998 (—). Undepleted discharge (-◆-) reflects estimated undepleted discharge of the Colorado and Gila rivers at the SIB. Sources: measured discharge prior to 1935 from Morrison *et al*., 1996; measured discharge 1935–1998 from IBWC; undepleted Colorado River flow from U.S. Bureau of Reclamation; undepleted Gila River flow based on annual estimate from U.S. Bureau of Reclamation (1952).

is now captured and used before reaching the river's mouth (Morrison *et al*., 1996). Figure 1 compares discharge at the Southerly International Boundary (SIB) with the estimated combined discharge of the undepleted Colorado and Gila rivers.

Yet, despite reports that the delta was a dead ecosystem where the Colorado River no longer reached the sea (Fradkin, 1981), agricultural drainage and the occasional space-building releases of Colorado River water from upstream reservoirs have prompted significant new growth of valuable native riparian and emergent wetland habitat, supporting the largest and most critical arid wetland in North America and sustaining avian and aquatic species of concern (Glenn *et al*., 1992, 1996; Luecke *et al*., 1999). Flood releases have also been strongly correlated with a rise in the shrimp catch in the Upper Gulf (Galindo-Bect *et al*., 2000), an indication of the renewed viability of an important estuary.

The gauge at the SIB (the southernmost point of the limitrophe dividing Baja California, Mexico from Arizona, U.S.A.), records discharge to the upstream extent of the delta. In nine years within the most recent 30 year period of record (1969-1998), annual discharge at the SIB has exceeded 1,000 x 10^6 m^3. Mean annual discharge at the SIB during this period measured 2,350 x 10^6 m^3 year^{-1}, while median discharge was 190 x 10^6 m^3 year^{-1} (δ= 4,400 x 10^6 m^3 year^{-1}). The Colorado River discharges to the delta when either or both of the following sets of conditions are satisfied: the elevation of Lake Mead on the Colorado River, or Painted Rock Reservoir on the Gila River, and projected run-off into that reservoir are both sufficiently high to trigger flood-control releases, and the timing and magnitude of such releases exceed the demands and diversion capacity of downstream diverters.

This study provides a more robust assessment of sources and quantities of discharge to the Colorado River delta than has been published previously, offering historical and recent records of discharge at several specific locations near the SIB, agricultural drainage entering the mainstem, as well as calculated discharge at several other locations, including the Cienega de Santa Clara and the mouth of the Colorado River at the upper Gulf of California. Due to data constraints, the study is limited to the calendar year period 1992 - 1998. To refine the assessment, the study distinguishes between years in which flood stage (estimated by Luecke *et al*., 1999 as 100-200 m^3 sec^{-1}) of the Colorado River was exceeded and those years in which it was not.

Description of the Study Area

The Colorado River delta lies in the Sonoran desert, characterized by low precipitation (54 mm $year^{-1}$) and high evaporation rates (2,046 mm $year^{-1}$) (IBWC, 1992-1998). This study employs the delta boundaries defined by recent literature (Valdés-Casillas *et al*., 1998; Luecke *et al*., 1999), encompassing a land area of roughly 600 km^2 along the border of the Mexican states of Baja California and Sonora. For the purposes of this study, the delta refers to the area downstream of Morelos Dam between the levees, plus the Rio Hardy wetlands northwest of the levee on the right bank, and the Cienega de Santa Clara (4200 ha) and El Indio (1900 ha) and El Doctor (750 ha) wetlands east of the levee on the left bank (Figure 2). The delta also commonly includes the intertidal zone along the final 19 km of the river, encompassing 440 ha (Luecke *et al*., 1999). Due to difficulties encountered in controlling for tidal effects, this study does not include the intertidal zone within the water balance.

The foot of Morelos Dam, 1.8 km downstream of the NIB, marks the uppermost limit of the delta, which extends downstream along the limitrophe dividing Baja California from Arizona. The upstream extent of the delta, characterized by willow (*Salix goodingii*) thickets and cottonwood (*Populus fremontii*)-willow gallery forests (Valdés-Casillas *et al*., 1998), is constrained within levees that were constructed to protect the surrounding agricultural areas from flooding. The area within the levees broadens downstream near the Colorado's confluence with the Rio Hardy, where the native riparian vegetation was supplanted by wetland vegetation and a higher proportion of non-native saltcedar (*Tamarix ramosissima*) (Luecke *et al*., 1999). Downstream of the confluence lies the intertidal zone, characterized by endemic saltgrass (*Distichlis palmerii*), affected by the extreme tides (amplitude > 8 m (Lavín *et al*., 1997)) of the Upper Gulf of California (Glenn *et al*., 1999).

The delta also commonly includes three wetland areas distinct from the mainstem system: the Cienega de Santa Clara and El Indio wetlands, characterized by dense stands of cattails (*Typha domingensis*), common reed (*Phragmites australis*) and bulrush (*Scirpus americanus*) (Glenn *et al*., 1992), and El Doctor wetlands, supporting 29 wetland plant species (Zengel *et al*., 1995). The Cienega, the largest of these distinct wetlands, has a total inundated area of 12,000 ha, of which some 4200 ha are vegetated (Luecke *et al*., 1999; Zamora-Arroyo *et al*., *this volume*). The Cienega lies in a depression formed by the Cierro Prieto fault, in a former arm of the Colorado River (Glenn *et al*., 1999). In the 1970s, agricultural drainage from Mexico's Riito Drain and local artesian springs supported a smaller (200 ha) wetland at the site. Agricultural drainage discharged behind the levee on the left bank of the Colorado River supported El Indio wetlands (Luecke *et al*., 1999). Artesian springs along the eastern edge of the delta sustain El Doctor wetlands (Glenn *et al*., 1999).

The timing, quantity, and quality of discharge through the delta affect vegetation differently. Riparian and wetland species have differing flow requirements, both over their individual life-cycles and across species. Native riparian vegetation occurring along the Colorado River mainstem,

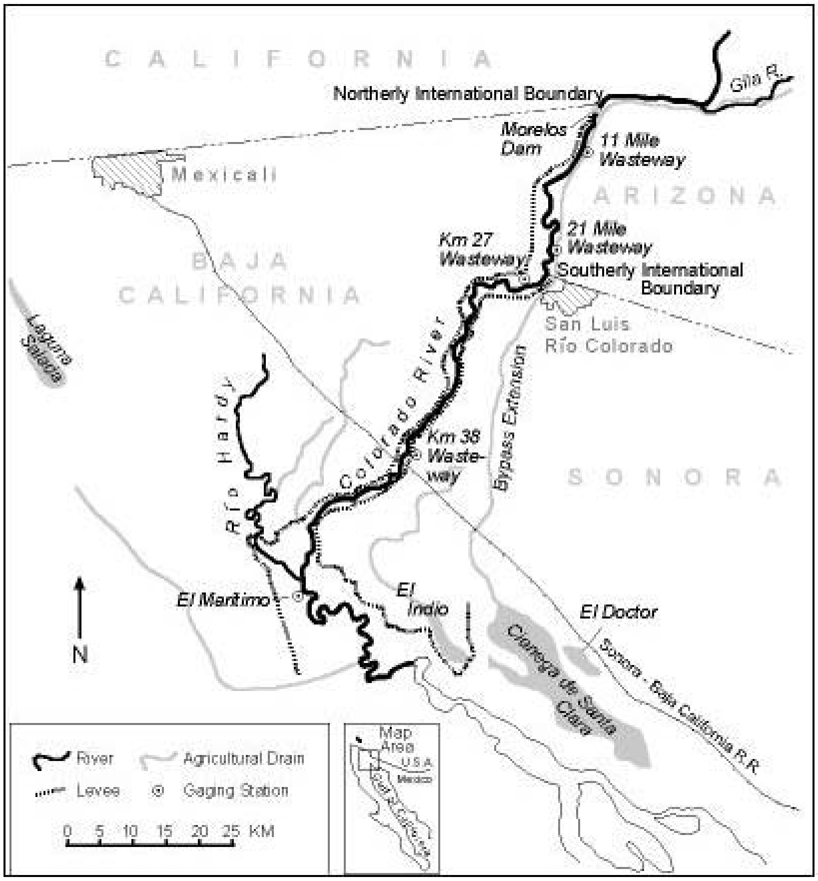

Figure 2. Major hydrological features of the Colorado River delta (after IBWC, 1992-1998).

such as Fremont cottonwoods (*Populus fremontii*) and Goodding's willow (*Salix gooddingii*), require overbank flooding to flush soils of accumulated salts (Glenn *et* al., 1998) and for seedling recruitment (Stromberg, 1993). Established cottonwood and willow seedlings depend upon the alluvial aquifer, rather than directly upon instream flows (Dawson and Ehleringer, 1991; Stromberg, 1993). Emergent vegetation, such as that occurring in the Rio Hardy wetlands and the Cienega de Santa Clara, depends upon available surface water (Glenn *et al*., 1992, 1996).

In its delta, the Colorado River was a low gradient, meandering stream with no firm channel: the downstream, broader reach of the floodplain is replete with oxbows and backwaters, vestiges of former channels (Sykes, 1937). The total length of the Colorado River from Morelos Dam to its mouth near Isla Montague, at the Upper Gulf of California, was about 150 km (C. Valdés-Casillas, pers. comm.). The maximum elevation of the river occurred at the base of Morelos Dam, with a streambed elevation approximately 32 meters above mean sea level (msl). On-going dredging operations in the limitrophe, administered by the binational International Boundary and Water Commission (IBWC), will lower streambed elevation by as much as 8 meters. The Rio Hardy, a former channel of the Colorado River (Sykes, 1937), runs 24 km to its mouth at the Colorado River, discharging primarily agricultural drainage from the Mexicali Valley (Valdés-Casillas *et al*., 1998). In flood years, water drained from the mainstem below the confluence with the Rio Hardy into the Laguna Salada basin, which has a minimum elevation of -3 m msl.

The flow of Colorado River water to Mexico and the delta is tightly controlled. The 1944 U.S.-Mexico Treaty on the Utilization of Waters of the Colorado And Tijuana Rivers and of the Rio Grande (1944 Treaty) commits the U.S. to deliver 1,850 x 10^6 m^3 of Colorado River water to Mexico each year, of which at least 1,678 x 10^6 m^3 is to be delivered at the NIB and the remainder may be delivered at the SIB near the mainstem. In years in which a surplus of water exists in excess of U.S. demands, the Treaty commits the U.S. to deliver up to an additional 246 x 10^6 m^3 of water to Mexico (Hundley, 1966).

A 1973 amendment to the 1944 Treaty, and resultant federal implementing legislation, led in 1977 to the discharge of brackish (>2900 ppm) groundwater (previously discharged into the mainstem) into an area in the southeastern edge of the delta, greatly expanding the extent of the Cienega de Santa Clara from some 200 ha to an estimated 20,000 ha (Glenn *et al*., 1992; Zengel *et al*., 1995).

While the institutional context controls the timing and quantity of Colorado River discharge, the physical infrastructure in and around the delta determines the location of deliveries. This infrastructure, displayed in Figure 2, includes Morelos Dam, a levee system, and agricultural drains and wasteways. Morelos Dam is a run-of-the-river diversion dam with no effective storage capacity. Instantaneous discharge in excess of Morelos Dam's diversion capacity of 226 m^3 sec^{-1}, and discharge in excess of agricultural and urban consumptive use orders, pass through the dam and into the mainstem. Between Morelos Dam and the SIB, the Eleven Mile Wasteway (5.1 km downstream of Morelos Dam) and the Twenty-one Mile Wasteway (28.0 km downstream) discharge agricultural drainage, from the Valley Division of the Yuma Project in Arizona, into the mainstem. On an emergency basis, Wellton-Mohawk drainage water has been discharged to a point immediately below Morelos Dam (IBWC, 1992-1998).

The IBWC measures combined mainstem discharge at the SIB (IBWC, 1992-1998). These records reflect discharge at the upstream boundary of the Colorado River mainstem portion of the delta (Glenn *et al*., 1996; Luecke *et al*., 1999), and have been used in other studies as a proxy for discharge into the Upper Gulf of California (Lavín and Sánchez, 1999; Galindo-Bect *et al*., 2000). Colorado River flow at the SIB over the period of record (1935-1998) was highly variable (mean = 3,272 x 10^6 m^3 $year^{-1}$; median = 1,237 x 10^6 m^3 $year^{-1}$; δ = 4,301 x 10^6 m^3 $year^{-1}$).

Some of the water Mexico diverts at Morelos Dam is conveyed via the Central Feeder Canal to a point 5 km downstream from the SIB, where it may be returned to the river via the KM 27 Wasteway on the right bank of the river or may be diverted to the Bacanora-Monumentos Canal system via the Sanchez Mejorada siphon, to irrigate fields in the San Luis Valley on the left bank of the river. Municipal effluent from the City of San Luís Río Colorado discharges to the Colorado River on the left bank of the river, near KM 27. The KM 38 Wasteway, 45.3 km downstream from the SIB and 1.3 km upstream from the railroad bridge, returns water from the Barrote Canal to the mainstem (IBWC 1992-1998). The Carranza and Principal Southern drains discharge directly, via gates in the levee, into the Colorado River, while the Nayarit, Cucapa, and Southern Collector drains discharge into the Rio Hardy. The Riito drain discharges into the Cienega, while the Plan de Ayala drain discharges into El Indio wetlands. The Main Outlet Drain Bypass Extension (Bypass Extension), diverting brackish (>3200 ppm) groundwater pumped from Arizona's Wellton-Mohawk Irrigation and Drainage District, runs 56 km from the SIB to the Cienega (Valdés-Casillas *et al*., 1998).

Material and Methods

This study developed a water balance for the Colorado River Delta using existing flow data, calculated system losses to evaporation and evapotranspiration (ET), and estimated outflows with a mass balance and historical records. Published discharge records (IBWC, 1992-1998) for the mainstem at the SIB and for the Bypass Extension at the SIB were supplemented by unpublished agricultural drainage records obtained from Mexico's Comisión Nacional de Agua (CNA) and by unpublished municipal discharge records from Mexico's Organismo Operador Municipal de Agua Potable, Alcantarillado y Saneamiento de San Luís Río Colorado (OOMAPAS). Losses due to evaporation and ET were calculated from published reports of vegetation type, extent, and density (Valdés-Casillas *et al*., 1998; Luecke *et al*., 1999; Zamora-Arroyo *et al*., *this volume*), Lower Colorado River Accounting System (LCRAS) ET coefficients (U.S. Bureau of Reclamation 1997, 1998), and published pan evaporation rates (IBWC, 1992-1998). Agricultural drainage flow records prior to the year 1992 and IBWC records after 1998 were not available, limiting the study to the period 1992-1998.

To refine the analysis, the study area was divided into three hydrologic sub-systems: the Colorado River mainstem complex, which includes the Rio Hardy; the Cienega de Santa Clara and the proximate El Doctor wetland; and El Indio wetlands. The temporal scale of the study was also broken down for the mainstem complex into flood years and non-flood years, based on the estimate of Luecke *et al*. (1999) that releases of 100-200 $m^3 sec^{-1}$ are necessary to achieve flood stage on the Colorado River mainstem below Morelos Dam. "Non-Flood Years" reflects means for the years 1992, 1994, 1995, and 1996. "Flood Years" reflects means for the years 1993, 1997, and 1998. Mean annual discharge at the SIB for Non-Flood Years was < 30 x 10^6 m^3; for Flood Years, mean annual discharge was markedly higher (> 2,500 x 10^6 m^3).

The study used a mass balance to characterize discharge through the study area. The mass balance equation (Owen-Joyce and Raymond 1996) can be described as:

$$Q_{ds} = Q_{us} + Q_{rf} + P + T_r - E - ET - \Delta S_a - Q_{sb},$$

where

Q_{ds} = flow at the downstream boundary
Q_{us} = flow at the upstream boundary
Q_{rf} = return flow to the river (from outside the region)
P = precipitation (on open water surfaces)
T_r = tributary inflow (local runoff)
E = evaporation from open water surfaces
ET = evapotranspiration
ΔS_a = change in aquifer storage
Q_{sb} = flow to sub-basin.

Note that there was no surface storage capacity at or below Morelos Dam. Total inflow, for the region as a whole or a particular sub-system, can be described as:

$$IF = Q_{us} + Q_{rf} + P + T_r.$$

Total outflow can be described as:

$$OF = Q_{ds} + E + ET + Q_{sb} + \Delta S_a.$$

Discharge at the upstream boundary (Q_{us}) is from published records (IBWC, 1992-1998) and from the CNA. Records of discharge at the SIB, 35 km downstream from Morelos Dam, were used as a proxy for discharge at the upstream boundary (Q_{us}). For the Cienega, recorded discharge of the MODE at the SIB (IBWC, 1992-1998) represents Q_{us}.

Records of agricultural and municipal drainage (Q_{rf}), where available, were obtained from CNA and from Valdés-Casillas *et al*. (1998), and estimated from data obtained from OOMAPAS, the municipal water agency for the City of San Luís Río Colorado. OOMAPAS provided records of deliveries for the years 1990, 1995, and 1999, and records of municipal discharge for the year 1999. Estimates of municipal effluent discharge to the river for the study period were based on an assumption of an annual growth rate in water consumption of 2.5%, the best fit for the records of water deliveries.

Precipitation (P) was calculated from precipitation records for the "Delta" and "Riito" stations, as reported by IBWC (1992-1998) and reported extent of open-water surfaces (Zamora-Arroyo *et al*., *this volume*). Records of precipitation and evaporation were incomplete for the "Delta" station for the years 1995 and 1996, so means for the mainstem complex did not include these years.

The levees minimize the direct influence of tributary runoff (T_r) on the mainstem, but runoff does discharge into the Rio Hardy. It was assumed that tributary runoff to the Cienega and to El Doctor and El Indio wetlands was negligible, due to greater permeability of soils between these areas and their headwaters. As noted, some (10^7 m^3 $year^{-1}$) of this water discharges to El Doctor wetlands through artesian springs (Glenn *et al*., 1996). Factors such as soil depth and permeability, vegetative cover, and rainfall intensity and duration affect runoff (Hely & Peck, 1964). Hely & Peck (1964) estimated runoff for the lower Colorado River-Salton Sea area, roughly 50 - 100 km north of the study area, by measuring initial soil infiltration and correlating this with soil type to project a runoff curve number. This runoff curve was then used to project runoff as a percentage of precipitation, ranging from effectively 0% for sandy alluvial soils, to roughly 8% for less permeable alluvial soils, to more than 20% for foothill/plateau areas with less permeable soils. This study estimates runoff at 8% of precipitation, to account for the lack of rainfall records for the mountain regions balanced against expected infiltration in the permeable alluvial soils between the base of the mountains and the hydrologic systems in this study. Accurate projections of runoff require records of finer temporal resolution than were available for this study, as well as analysis of the permeability of soils underlying ephemeral streams (Hely & Peck, 1964). Therefore, the calculations of tributary runoff are offered as a general estimate.

Evaporation (E) from open water surfaces was calculated from total area of open water (Luecke *et al*., 1999; Zamora-Arroyo *et al*., *this volume*) and reported pan evaporation rates for the "Delta" and "Riito" stations in Mexico, as reported by the IBWC (1992-1998), using a pan-to-lake coefficient of 0.60 (Owen-Joyce and Raymond, 1996). The 1997 flood event inundated the mainstem floodplain between the levees (Luecke *et al*., 1999), greatly increasing the extent of open-water surface area (30,000 ha) subject to evaporation and infiltration. Evapotranspiration (ET) rates for wetland vegetation were calculated from reports of vegetation density, extent, and type (Valdés-Casillas *et al*., 1998) and LCRAS (U.S. Bureau of Reclamation 1997) ET coefficients, for the year 1997. Established riparian vegetation was assumed to draw from the alluvial aquifer (Dawson and Ehleringer, 1991; Stromberg, 1993). ET for riparian vegetation in the delta was estimated for purposes of comparison but was not included as part of the surface water balance.

Change in storage in the alluvial aquifer (ΔS_a) for non-flood years was based on estimates of ΔS_a for the reach of the river from Imperial Dam to Morelos Dam, (U.S. Bureau of Reclamation, 1998). For flood years, ΔS_a was calculated from extent of inundated area and reported infiltration rates for the permeable alluvial soils characteristic of the floodplain. Measured initial infiltration for dry or slightly moist soils was reported at 2.5 cm for a 30 minute period (Hely & Peck, 1964).

Groundwater as a distinct source was not assessed as part of this study. Groundwater, applied as irrigation and delivered for municipal use, contributes to the water balance in the form of agricultural drainage and municipal effluent. These contributions are included within the estimates of agricultural and municipal discharge to the delta but are not identified separately. Actual records of groundwater extraction and recharge for the study area were not available. Several on-going studies seek to better assess the source, extent, quality, and discharge of groundwater in the region. Such information will greatly improve understanding of the quantity and movement of water in the region.

In flood years with high discharge, water from the Colorado River mainstem has discharged into the Laguna Salada basin (Q_{sb}) (Luecke *et al*., 1999). The Laguna Salada is also the drainage basin for the Sierra de Juarez range to the west, and for the Sierra de los Cucapas range to the east, challenging efforts to account for the source of standing water in the basin. A review of Landsat 4 Multispectral Scanner Satellite images (path 39 row 38) revealed standing water in the Laguna Salada in 1993, 1997, and 1998. Personal observation (November, 1998) by one of the authors noted water flowing through a drainage canal to the Laguna, but discharge was not determined. Discharge to the Laguna Salada was estimated based on anecdotal observations, an unpublished report (Compean-Jiménez *et al*., no date), that estimated the 1984 extent of the inundated area at 40,000 ha, with a maximum depth of 4 m and a volume of 730 x 10^6 m^3, and from Valdés-Casillas *et al*. (1998), who estimated the extent of the Laguna Salada in 1997 at 10,000 ha.

El Indio wetland was constrained by the levee on the left bank of the river, though water drained to the mainstem through a gate in the levee until 2000. Discharge at its downstream boundary (Q_{ds}) was calculated. Zengel *et al*. (1995) note that half of the inflow water to the Cienega exited the vegetated portion, though Glenn *et al*. (1992) note that the southern portion of the Cienega was essentially an evaporative basin with connection to the Upper Gulf of California only during periods of highest tides, indicating that flow at the downstream border for the Cienega was effectively zero.

For the mainstem, discharge at the downstream border (the river's mouth, at the Upper Gulf of California) has been estimated in the literature to be equivalent to discharge at the SIB (Lavín and Sánchez, 1999; Galindo-Bect *et al*., 2000); no gauge currently records these discharge. The last gauging station on the Colorado River, at El Marítimo, was destroyed by the 1983 Colorado River floods. Flow data at this station are only available for the period January, 1960 through July, 1968, when it was determined that tidal influences distorted the readings (CILA, 1968). Station records subsequent to 1968 are limited to mean daily gage height, which reflect tidal influence as well as mainstem discharge and agricultural drainage. Table 1 compares annual records from El Marítimo with those from the SIB.

Linear regressions were run for daily discharge records (m^3 sec^{-1}) for the SIB and El Marítimo gauging stations for the years 1960 and 1965. The strongest correlation ($r^2 = 0.944$) for 1960 occurred with a two day lag between the two stations, with a regression line described by $y = 0.834x + 1.42$. The strongest correlation ($r^2 = 0.66$) for 1965 occurred with a two day lag between the two stations, with a regression line described by $y = 0.516x + 0.94$. Several factors, including

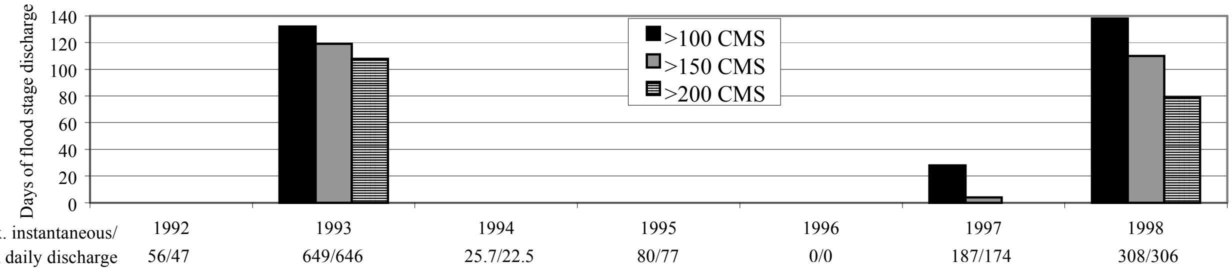

Figure 3. Total days of flood stage discharge at the SIB, 1992–1998, with annual maximum instantaneous and daily discharge, in $m^3\ s^{-1}$ (IBWC, annual).

the construction of the levees, changing irrigation practices, the variability of discharge to the Laguna Salada, and the questionable accuracy of the records themselves, challenge efforts to use these calculated values to estimate discharge at the mouth of the Colorado River. However, these correlations did provide a value to compare the magnitude of discharge at the Upper Gulf of California calculated by using the water balance equation.

Results

Luecke *et al*. (1999) estimate that releases of 100-200 $m^3\ sec^{-1}$ are necessary to achieve flood stage on the Colorado River mainstem below Morelos Dam. Records of mean daily discharge at the SIB (IBWC, 1992-1998) were compiled to determine whether the year was a flood or non-flood year. Figure 3 displays the total number of days, by year, within the study period in which mean daily discharge equaled or exceeded thresholds of 100, 150, and 200 $m^3\ sec^{-1}$ (CMS). Along the x axis, below each year, are the annual maximum instantaneous and maximum mean daily discharge, in $m^3\ sec^{-1}$. Note that no measurable discharge was recorded at the SIB in 1996. Maximum daily discharge occurred in January to March of each year.

Table 2 shows the values of the factors aggregated as return flow for the mainstem, disaggregated into Flood and Non-Flood Years. The Colector del Sur drain, reflecting contributions from numerous secondary and tertiary drains serving the lower Mexicali Valley, discharges to the Rio Hardy. The Principal del Sur drain, reflecting contributions from the Carranza drain and other secondary and tertiary drains, discharges to the Rio Hardy-Colorado River delta wetland complex (Valdés-Casillas *et al*., 1998). The marked increase in discharge through the KM 27 and KM 38 wasteways between flood and non-flood years was particularly notable. The similarity in mean annual return flow between flood and non-flood years reflects increased groundwater extraction during non-flood years.

Table 3 shows the values for the variables in the water balance equation for the Colorado River mainstem for the years 1992-1998, disaggregated into Flood and Non-Flood Years. Q_{ds} was calculated from the El Maritimo regression described previously, generating The non-flood year displays a large undistributed residual, reflecting markedly greater inflows than outflows. This discrepancy may be due to one or more factors, including greater evaporation and infiltration than calculated, unrecorded diversions from the mainstem below the SIB, and consumption of surface water by other vegetation, or errors in the calculated Q_{ds}. Most notable is the difference, of two orders of magnitude, in discharge at the upstream boundary. Evaporation from open water surfaces and change in storage both reflect the effects of inundation of the floodplain, which greatly increased the potential for infiltration and evaporation. Change in storage here represents only gains, and does not reflect losses due to phreatophytes, sub-surface flows, or other factors. ET only reflects that of emergent wetland vegetation; mean annual ET for the mainstem was estimated at 210 x 10^6 m^3.

Table 4 shows the values for the variables in the water balance equation for the Cienega de Santa Clara for the years 1992-1998. The estimated losses to MODE discharge due to evaporation and seepage between the SIB and the Cienega (0.39 x 10 m^6 $year^{-1}$) represent less than 0.4% of total discharge and were not included in the water balance. In 1993, discharge through the MODE was disrupted by the Gila River flood event. Total recorded discharge at the SIB in the bypass extension that year was 75.8 x 10^6 m^3. In 1993, Wellton-Mohawk ceased discharging to the MODE on February 21 (contributing 25% of total annual discharge). From February 21 through May 30 the MODE contained Gila floodwaters (58% of total discharge); discharge in June through November 4 were from Yuma Valley groundwater wells (17%), and for the remainder of the year the discharge consisted of San Luis, Arizona effluent (<1%) (IBWC, 1993). The interruption in flows through the MODE decreased the size of the Cienega and led to the mortality of 60-70% of the marsh foliage (Zengel *et al*., 1995).

Artesian springs at the southeastern edge of the delta sustain pocket wetlands, many of extremely limited area yet supporting greater plant diversity (Ezcurra *et al*., 1988) than the wetlands sustained by agricultural drainage (Luecke *et al*., 1999). Glenn *et al*. (1996) estimate that these artesian springs discharge approximately 10^7 m^3 $year^{-1}$.

Table 5 shows the mean annual values for the variables in the water balance equation for El Indio wetlands for the years 1992-1998. The Plan de Ayala drain, serving irrigated areas in the San Luis valley, discharges to a point behind the levee on the left bank of the Colorado River. CNA records this drain served as discharge at the upstream boundary for the system. The results of the mass balance equation for El Indio reflect the limited data available and uncertainty regarding the fate of water entering the system. Q_{ds} was derived from the mass balance. The residual for this system, at 75% of total inflow, may be explained partially by uncalculated infiltration and additional evaporation. An additional source of outflow from the system could have taken the form of seepage through the levee into the mainstem, but this has not been verified.

Discussion

Discharge through the delta, and particularly through the mainstem Colorado River-Rio Hardy complex, demonstrated marked variability between flood and non-flood years. Flood years also showed greater discharge to the mainstem from wasteways and agricultural drains relative to non-flood years, consistent with increased deliveries of Colorado River water to Mexico in surplus years. As a result of increased surface area due to inundation of the floodplain, outflows via evaporation and infiltration also increased dramatically during flood years.

The most consistent source of water to the delta, both as a whole and for each of the three sub-systems, was agricultural drainage. Such drainage provided the overwhelming majority of discharge to the Cienega de Santa Clara and El Indio wetlands, and more than 40% of total inflows to the Colorado River-Rio Hardy mainstem complex in non-flood years. Particularly notable for the mainstem was the contribution of wasteways (22%) during non-flood years. With the exception of El Doctor wetlands, the contribution of local sources of water was negligible.

The contribution of agriculture drainage is consistent with its historic role of providing a baseline against the variability of mainstem Colorado River discharge. Since 1960, agricultural drainage

Table 2. *Return flows to the Colorado River mainstem below Morelos Dam, 1992–1998. Mean annual discharge (10^6 m^3)*

Source	Non-flood years	Flood years
KM 27 wasteway	22	220
San Luis Rio Colorado effluent nr. Km 27	12	12
KM 38 wasteway	1·3	6·5
Colector del Sur drain	11	12
Principal del Sur drain	24	29
Total return flows to the river (Q_{rf})	70	280

Table 3. *Water balance for the Colorado River mainstem below Morelos Dam, 1992–1998. Mean annual discharge (10^6 m^3)*

Inflows and outflows	Non-flood years	Flood years
*Wasteways at Limitrophe**	*3·0*	*3·1*
Discharge at upstream boundary (Q_{us})	28·3	2620
Return flows to the river (Q_{rf})	70	280
Precipitation (P)	0·2	0·2
Tributary inflow (T_r)	0·6	0·5
Evaporation from open water surfaces (E)	4	270
Evapotranspiration (ET)	9	9
Change in aquifer storage (ΔS_a)	5	720
Discharge to Laguna Salada sub-basin (Q_{sb})	0	200
Discharge at the downstream boundary (Q_{ds})	26	1700

**Wasteways at Limitrophe* aggregates the records of the three wasteways that discharge into the limitrophe; these flows are included as part of the 'Total at SIB'.

and returns from irrigation canals have provided greater discharge (310 x 10^6 m^3 $year^{-1}$) than median discharge from the mainstem (180 x 10^6 m^3 $year^{-1}$) (IBWC, 1998). However, the location of this discharge, primarily into the Rio Hardy wetlands, limited the potential benefits of agricultural drainage to native riparian vegetation in the upper reaches of the delta.

Of potentially greater benefit to this vegetation was the contribution to the mainstem from the two wasteways and from San Luís Río Colorado effluent. Luecke *et al*. (1999) estimate the annual discharge requirements for the upper 100 km reach of the mainstem at 40 x 10^6 m^3. This total was not met in either 1994 (31 x 10^6 m^3) or 1996 (14 x 10^6 m^3), though in other non-flood years the combination of mainstem discharge through Morelos Dam, wasteways, and municipal effluent exceeded this target below the SIB. Water quality was not assessed in this study, though it is assumed that the effluent is of lower quality than the wasteway discharge. It should be noted that wasteway discharge varied markedly on a monthly basis, from 0 in July to more than 47 x 10^6 m^3 in October, 1998 for the KM 27 wasteway (IBWC, 1998).

Flood stage was exceeded for the mainstem in three of the seven years of the study period. Inundation of the floodplain has important implications both for recruitment of native riparian vegetation and for recharge of the alluvial aquifer. Flood stage for the mainstem below Morelos Dam has not been determined definitively. A review of recorded mean daily discharge at the SIB indicated that discharge of 100 m^3 sec^{-1} or less may be sufficient to promote inundation of the floodplain, as was reported for February 21, 1997 (Luecke *et al*., 1999). By this date, records of mean daily discharge had exceeded 100 m^3 sec^{-1} on seven occasions, with an additional nine occurrences exceeding 80 m^3 sec^{-1}. Inundation of the floodplain has not been reported for 1995, which witnessed a maximum instantaneous discharge of 80 m^3 sec^{-1} and a maximum mean daily discharge of 77 m^3 sec^{-1}. Further investigation of flood stage for the mainstem, and how this stage varies across space, is warranted.

Table 4. *Water balance for the Cienega de Santa Clara, 1992–1998*

Inflows and outflows	10^6 m^3
Discharge at upstream boundary (Q_{us})	128
Return flow (Q_{rf})	16
Precipitation (P)	2
Tributary inflow (T_r)	0
Evaporation from open water surfaces (E)	84
Evapotranspiration (ET)	60
Change in aquifer storage (ΔS_a)	2
Discharge at the downstream boundary (Q_{ds})	0

Table 5. *Water balance for El Indio Wetlands, 1992–1998*

Inflows and outflows	10^6 m^3
Discharge at upstream boundary (Q_{us})	18
Return flow (Q_{rf})	0
Precipitation (P)	0·2
Tributary inflow (T_r)	0
Evaporation from open water surfaces (E)	1
Evapotranspiration (ET)	4
Change in aquifer storage (ΔS_a)	13
Discharge at the downstream boundary (Q_{ds})	0

While records existed for many of the sources of inflow, sources of outflow were generally estimated from other records. Evaporation and infiltration for the mainstem varied markedly between flood and non-flood years, due to the increase in surface area of open water. Evapotranspiration rates varied across the sub-regions, reflecting the greater proportion of emergent wetland vegetation at the Cienega relative to the mainstem complex. The estimated discharge at the downstream boundary for the mainstem suggests that recorded discharge at SIB may not be a reliable indicator of total discharge through the system.

The study was hampered by the limited availability of outflow data, challenging efforts to balance the water budget. Most notable was the lack of information on depth to the alluvial aquifer, groundwater movement, infiltration rates, and discharge to the Laguna Salada. The magnitude of shallow groundwater consumed by non-wetland vegetation in the delta, estimated at 210 x 10^6 m^3, suggests that infiltration during flood years may recharge the aquifer. These data gaps are significant. Filling these gaps will improve understanding of discharge through the system.

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